Report on the Workshop on

"Dynamics of Structures and

Intermittencies in Turbulence"

Arizona State University

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1. Synopsis

This workshop brought together some 45 researchers at the forefront of the physics and mathematics of Coherent Structures and Intermittencies in Turbulence. It was organized along the following main axes:

- Theoretical and Computational Aspects of Structures and Intermittencies;
- Experiments on Structures and Intermittencies;
- Dynamical Systems and Turbulence.

Three special panel discussion sessions enabled a more synthetic perspective on:

- transitions and structures in Wakes;
- transitions and structures in Boundary Layers;
- the connection between Dynamical Systems and Turbulence.

Some 20 graduate students did attend the Workshop.

2. Vortex Dynamics as a Paragon of Dynamics of Structures

S. Orszag discussed three-dimensional vorticity dynamics from the perspective of singularities and structures. The search for singularities of Euler equations has covered Taylor-Green vortices; Axisymmetric flows with swirl; and vortex reconnections (vortex topology changes enabled by viscosity). Singularities can be avoided only if vorticity and rate of strain do not lose correlation with each other. Several models of vortex reconnection test different vorticity-strain couplings. The two-fluid picture of turbulence (She, Jackson and S. Orszag) focuses on coherent large-scale amplitude vortex structures (with rare vortex reconnections), yet responsible for small-scale intermittency and anomalous probability distributions.

R. Caflisch presented vortex stretching instabilities for axi-symmetric flows with swirl; the basic flow is an axi-symmetric vortex sheet (or shear layer) with pure swirling flow; complex vortex reconnections are observed, with possible singularity formation (at least in computer experiments).

H. Aref discussed vortex interactions as a Dynamical System, from the perspective of the "observational," "inverse" and "direct" problems. A salient historical review was a highlight. From the point of view of a Dynamical Systems Picture, the "good news" includes:

- several model "formats" of vorticity/vortices exist: points, patches, filaments, rings, etc.;
- Dynamical systems using these formats are known: point vortex equations, contour dynamics, rings, etc.;

the "bad news" is:

- interactions of vortices lead to "topology changes": vortex merging, reconnection, linking, etc.;
- degrees of freedom in the dynamical system are changed: merging, dipole formation, realignment within rings ....

H. Aref's recommendation:

- *Consider dynamical systems with sudden changes in degrees-of-freedom.*

F. H. Hussain focussed on understanding turbulence mechanisms via vortex dynamics. The main issues were: reconnection (cascade and mixing), core dynamics (helical wave decomposition), large-scales vs. small scales interactions. Other issues addressed the pitfalls of flow visualization; transition and cascade suppression; validity of local isotropy assumption. An experimental surprise on anti-diffusion was presented (work with M.

Goldshtik). Hussain restated a clear-cut definition of coherent structures (C.S.): these are flow sub-domains with spatially phase-correlated vorticity; the remainder corresponds to incoherent turbulence. New cascade mechanisms are associated with vortex reconnections and breakdowns.

3. Theory of Intermittencies

Z. S. She developed a two-fluid model for fully-developed turbulence, within the context of structures (C.S.) and non-Gaussian statistics. The two-fluid model decomposes turbulence into random eddies plus coherent structures; it is antithetical to multi-fractal models. Structures are vested with dissipation, intermittency, non-Gaussianity and quasi-singularity; they are subject to high fluctuation, distortion by a self-generated field. Distortion is an additional process superposed on a strongly mixing cascade (linear Langevin process). The theoretical model realizes a mapping from an unstretched Langevin field to a stretched turbulent field. The model admits strong intermittency solutions, and fits very well (computed) Probability Distribution Functions (P.D.F.) of transverse velocity gradients in isotropic turbulence. Self-similarity is a key intrinsic property. This is in contrast with multifractal models, where the turbulent field is only locally self-similar.

Such multifractal models were strongly attacked by P. Dimotakis, both from the mathematical and experimental perspectives; one key argument is the non-preservation of fractal dimensions by projections and/or sections.

R. Kraichnan addressed open problems on Non-Gaussian statistics of P.D.F.'s as a signature of structures in turbulence (work with Z. S. She).

U. Frisch presented a new prediction of the multifractal model for fully developed turbulence, for the intermediate dissipative range.

V. Zakharov presented joint work with A. C. Newell on the dynamics of singularities in optical (e.g., lasers) turbulence; the issue is how much of this can be carried out to other regimes of turbulence?

4. Boundary Layer and Shear Turbulence.

W. S. Saric presented an array of experimental results on transitions and instabilities in boundary layers, including:

- Surface non-uniformity effects on boundary-layer stability and transition;
- crossflow instabilities and transition;
- Tollmien-Schlichting Receptivity;
- Görtler vortices over wavy walls

These were performed at the "Unsteady Wind Tunnel" Laboratory at A.S.U.

H. Reed presented theoretical results on the role of initial conditions on the evolution of unstable waves leading to turbulence in open systems. Whereas the boundary layer is an open system, processes of transition to turbulence are highly affected by initial and freestream conditions. The key issue is: why does a discrepancy occur between experiments and theory/computations regarding naturally occurring subharmonic modes? According to H. Reed, without streamwise vortices, computation supports theory; but with streamwise vortices, computation supports experiments. Receptivity is a mechanism by which external forced disturbances enter the boundary layer and generate unstable waves leading to turbulence. Natural receptivity is linked with freestream sound and vorticity; localized receptivity mechanisms include wall roughness, wall suction strips, discontinuity in curvature, shock/boundary-layer interactions. One finds that disturbance response is linear with freestream amplitude; a sharper leading edge is less "receptive"; and subcritical Tollmien-Schlichting wave growth is observed.

C. Van Atta addressed the problem of local isotropy and scaling of the smallest scales of turbulent scalar and velocity fields:

- the Kolmogorov theory of local isotropy is in fundamental disagreement with both laboratory experiments and geophysical observations;
- resolution of the conflict: isotropy does exist! This is achieved via a theory for spectra of gradients (density gradient spectra and correlations, anisotropy of density gradients);

- destruction of local isotropy is achieved by stable stratification (ocean data);
- this anisotropy can produce discrepancies in the dissipation estimates and induces limits of extended Kolmogorov scaling.

Methods of Proper Orthogonal Decomposition (P.O.D.) a.k.a. Karhunen-Loeve or Lumley methods were discussed by L. Sirovich, N. Aubry, I. Kevrekidis and M. Kirby; the goal is to extract computationally coherent structures from a complex turbulent field (experimental and numerical). This was extensively discussed by K. Ball in the context of turbulent channel flows and wall-bounded turbulence. Channel flow empirical eigenfunctions (P.O.D.'s) are computed; less than 20% of the modes are kinematically degenerate, but they account for more than 75% of the energy (1000 modes are needed to capture 95% of the energy). A finite-approximation splits the reconstructed flow between these degenerate modes and the propagating modes. Propagating plane waves are not necessarily independent of the observed coherent structures (large eddies, various vortex structures, etc.). Spatial structures thus extracted from the flow do include oblique plane waves, streamwise vortices, and shearing motions. Interaction of these plane waves appears to be essential to the local production of turbulence via bursting or sweeping events. Propagating modes may act like triggers.

5. Dynamical Systems and Turbulence

First, G. Broze defeated conventional wisdom by linking the spatiotemporal dynamics of Free Shear Flows with *closed* dynamical systems. For such open flows, the major difficulties are:

- these flows are spatially developing,
- they are convectively unstable.

The traditional idea of an open flow is that it is open to mass flow. G. Broze suggests that it is in fact *open to information*, that is, receptive to external perturbations. The classification between open and closed is a continuum, not a dichotomy. How can we get intrinsic dynamics from an *open* convectively unstable system? The key is "Global Resonance" or feedback via global pressure waves. The degree of "closedness" is proportional to the ratio of feedback to noise. In such "closed" open convectively unstable systems, one can pin down periodicity, period-doubling and intermittency phenomena. Hence, physically open systems may be dynamically closed, and low-dimensional chaos can occur in such systems!

At the mathematical level, M. Kwak demonstrated finite-dimensional inertial forms for the 2D Navier-Stokes equations in a closed geometry (periodic cells); in essence, it proves that a large, but *finite system* of Ordinary Differential Equations admits the same long-time dynamics than the 2D Navier-Stokes equations. Mathematically, they admit the same global attractor. Kwak uses a nonlinear transform which mixes both large and small spatial scales. Unfortunately, the method does not carry over to domains with no-slip physical boundary conditions.

A. Eden presented a joint work with C. Foias, B. Nicolaenko and R. Temam on "Inertial Sets" or "Exponential Attractors." Such dynamical objects encompass both the ultimate asymptotic states and the *slow-transient dynamics*; they are physically relevant to Navier-Stokes turbulence, and their mathematical existence is rigorously proven even for no-slip boundary conditions (in 2D geometry). They are fractal objects, as opposed to smooth "Inertial Manifolds," whose existence is still unproven and even questionable for Navier-Stokes. Finally, Inertial Sets are exceedingly robust and stable under numerical approximations and/or errors. These are the objects which we actually compute in large-scale numerical experiments on turbulence.

G. Sell presented results on global attractors for 3D Navier-Stokes equations in thin slabs (work with G. Raugel). The challenge is to prove that there cannot be any vortex singularities past some finite transient time; hence a fractal asymptotic attractor exists. The global mathematical regularity of 3D Navier-Stokes solutions is otherwise an outstanding mathematical problem. This work gives the first proof of global regularity with large initial data, in the context of thin slab geometry. The 3D attractor is then close to a 2D attractor.

6. Panel on the Connection between Dynamical Systems and Turbulence

The core conclusions were that:

- dynamical systems give good interpretation of transitions in closed systems;
- much more work has to be done in transition in open systems;
- is chaos for spatially extended Partial Differential Equations the same as in temporal dynamical systems?
- the dynamical systems approach should tie more with the classical statistical approach to turbulence;
- for more developed (but not yet fully developed!) turbulence, what is the linkage between dynamical systems and the dynamics of *large-scale coherent structures*?

Schedule of Sessions

Workshop on "Dynamics of Structures and Intermittencies in Turbulence"

ENGINEERING CENTER, ROOM EC G-324

MONDAY, MAY 20

Morning Session:	Theoretical and Computational Aspects of Structures and Intermittencies in Turbulence, I
9:00 – 9:15	Welcome and remarks
9:15 – 9:55	**Steve Orszag** Three-Dimensional Vorticity Dynamics: Singularities, Structures and all that ...
10:00 – 10:40	**Zhen-Su She** Structures and Non-Gaussian Statistics in Turbulence
10:45 – 11:15	Break
11:15 – 11:55	**Helen Reed** Role of Initial Conditions on Unstable Waves Evolving to Turbulence in Open Systems: I Navier-Stokes Simulations
12:00 – 12:40	**Hassan Aref** Vortex Interactions as a Dynamical System
Afternoon Session:	Dynamical Systems and Turbulence, I
2:00 – 2:40	**Russell Caflisch** A Vortex Stretching Instability for 3D Axisymmetric Flows with Swirl
2:45 – 3:25	**Iannis Kevrekidis** Approximate Inertial Manifolds and Proper Orthogonal Decomposition Methods in Complex Geometries
3:30 – 4:00	Break
4:00 – 4:40	**Gerard Iooss** Some New Results on Water Wave Dynamics
4:45 – 5:15	**Emily Stone** Heterclinic Cycles, Exponential Tails and Intermittency in a Turbulent Boundary Layer
6:00 - 7:30	**Social Hour and Reception** Tempe Mission Palms Sheraton (No Host Bar)

TUESDAY, MAY 21

Morning Session:	Proper Orthogonal Decomposition Methods
9:00 – 9:40	**Larry Sirovich** Dynamics in Wall Bounded Turbulence
9:45 – 10:25	**Nadine Aubry** Analysis of Space-Time Complexity in the Transition and Turbulence
10:30 – 11:00	Break
11:00 – 11:40	**Michael Kirby** Viewing the Geometry of Phase Space in Terms of Optimal Bases
11:45 – 12:25	**Ken Ball** Dynamics of Coherent Structures and Waves in the Turbulent Boundary Layer
Afternoon Session:	Experiments on Structures and Intermittencies, I
2:00 – 2:40	**Fazle Hussain** Understanding Cascade Mechanisms through Vortex Dynamics
2:45 – 3:25	**Charles Van Atta** Local Isotropy and Scaling of the Smallest Scales of Turbulent Scalar and Velocity Fields
3:30 – 4:00	Break
4:00 – 4:40	**Paul Dimotakis** Fractals, Dimensional Analysis and Similarity in Turbulence
4:45 – 5:30	**Dan Lathrop** The Transition to Fully Turbulent Couette-Taylor Flow

WEDNESDAY, MAY 22

Morning Session:	Experiments on Structures and Intermittencies, II
9:00 – 9:40	**William Saric** Role of Initial Conditions on Unstables Waves Evolving to Turbulence in Open Systems: II Navier-Stokes Experiments
9:45 – 10:25	**H. Fasel** (to be announced)
10:30 – 11:00	Break
11:00 – 11:40	**Jerry Gollub** Film Flow Instabilities and Spatiotemporal Dynamics
11:45 – 12:35	**Panel 1:** Transitions and Structures in Wakes
Afternoon Session:	Tour of Laboratories Free Time

THURSDAY, MAY 23

Morning Session:	Theoretical and Computational Aspects of Structures and Intermittencies in Turbulence, II
9:00 – 9:40	**Uriel Frisch** A New Prediction of the Multifractal Model for Fully Developed Turbulence: The Intermediate Dissipative Range
9:45 – 10:25	**Alan Newell** The Turbulence of the Nonlinear Schrödinger Equations
10:30 – 11:00	**Break**
11:00 – 11:30	**Basil Nicolaenko** Computer Movies of Turbulent 2D Forced Flows: Vortex Dynamics, Chaos, and all that ...
11:30 – 12:30	**Panel 2:** Transitions and Structures in Boundary Layers
Afternoon Session:	Dynamical Systems and Turbulence, II
2:00 – 2:35	**Minkyu Kwak** Finite Dimensional Inertial Forms for the 2D Navier-Stokes Equations
2:40 – 3:15	**Alp Eden** Inertial Sets and Exponential Attractors for 2D Navier-Stokes Equations
3:20 – 3:50	**Break**
3:50 – 4:30	**George Sell** Global Attractors for the Three Dimensional Navier-Stokes Equations in Thin Domains
4:35 – 5:15	**Michael Jolly** Bifurcation Computations on Approximate Inertial Manifolds for 2D Navier-Stokes Flows
5:20 – 5:55	**Alex Mahalov** Resonances in the Hagen-Poiseuille Problem
7:30 –	**Workshop Banquet, T.B.A.**

FRIDAY, MAY 24

Morning Session:	
9:00 – 9:40	**Vladimir Zakharov** Collapses and Intermittency in Optical Turbulence
9:45 – 10:25	**Robert Kraichnan** Probability Distributions and the Physics of Intermittency: Recent Results and Open Problems
10:30 – 11:00	**Break**
11:00 – 11:40	**Ciprian Foias** A Canonical Normal Form for the Navier-Stokes Equations
11:45 – 12:35	**Panel 3:** The Connection between Dynamical Systems and Turbulence
Afternoon Session:	Free